Short Paper

ACEEE Int. J. on Electrical and Power Engineering , Vol. 5, No. 1, February 2014

Artificial Intelligence Technique based Reactive Power Planning Incorporating FACTS Controllers in Real Time Power Transmission System

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***Abstract*-Reactive Power Planning is a major concern in the operation and control of power systems This paper compares the effectiveness of Evolutionary Programming (EP) and New Improved Differential Evolution (NIMDE) to solve Reactive Power Planning (RPP) problem incorporating FACTS Controllers like Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Unified power flow controller (UPFC) considering voltage stability. With help of Fast Voltage Stability Index (FVSI), the critical lines and buses are identified to install the FACTS controllers. The optimal settings of the control variables of the generator voltages,transformer tap settings and allocation and parameter settings of the SVC,TCSC,UPFC are considered for reactive power planning. The test and Validation of the proposed algorithm are conducted on IEEE 30–bus system and 72-bus Indian system.Simulation results shows that the UPFC gives better results than SVC and TCSC and the FACTS controllers reduce the system losses.**

***Keywords*-FACTS Devices, SVC, TCSC, UPFC , Reactive power planning,Fast Voltage Stability Index, Evolutionary programming, Differential Evolution**.

I. Introduction

One of the most challenging issues in power system research, Reactive Power Planning (RPP).Reactive power planning could be formulated with different objective functions[2] such as cost based objectives considering system operating conditions.Objecives can be variable and fixed VAr installation cost,real power loss cost and maximizing voltage stability margin. Reactive power planning problem required the simultaneous minimization of two objective functions. The first objective deals with the minimization of real power losses in reducing operating costs and improve the voltage profile. The second objective minimizes the allocation cost of additional reactive power sources. Reactive power planning is a nonlinear optimization problem for a large scale system with lot of uncertainties.During the last decades, there has been a growing concern in the RPP problems for the security and economy of power systems [1-2].

Conventional calculus based optimization algorithms have been used in RPP for years . Recently new methods on artificial intelligence have been used in reactive power planning.Conventional optimization methods are based on successive linearization[12] and use the first and second differentiations of objective function. Since the formulae of RPP problem are hyper quadric functions, linear and quadratic treatments induce lots of local minima.The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for better utilization of existing systems. Modern power systems are facing increased power flow due to increasing demand and are difficult to control.

The authors in [14] discussed a hierarchical reactive power planning that optimizes a set of corrective controls ,such that solution satisfies a given voltage stability margin.Evolutionary algorithms(EAs) Like Genetic Algorithm (GA),Differential Evolution(DE),and Evolutionary planning (EP)[15,16] have been widely exploited during the last two decades in the filed of engineering optimization.They are computionally efficient in finding the global best solution for reactive power planning and will not to be get trapped in local minima.Such intelligence modified new algorithms are used for reactive power planning recent works[12,13].

Modern Power Systems are facing increased demand and difficult to control.The rapid development to fast acting and self commutated power electronics converters ,well known Flexible AC Transmission Systems (FACTS),introduced by Hingorani.[5],are useful in taking fast control actions to ensure the security of power system. FACTS devices are capable of controlling the voltage angle and voltage magnitude at selected buses and line impedances of transmission lines.

In this paper, the maximum loadability[8] is calculated using FVSI. The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At this point, the connected load at the particular bus is considered as the maximum loadability. The smallest maximum loadability is ranked as the highest.This paper proposes the application of FACTS controllers to the RPP problem. The optimal location of FACTS controllers is identified by FVSI and the EP is used to find the optimal settings of the FACTS controllers.

The Proposed FVSI based DE Algorithm in comparing with EP algorithm for reactive power planning achieves the goal by setting suitable values for transformer tap settings

DOI: 01.IJEPE.5.1.8

ACEEE Int. J. on Electrical and Power Engineering , Vol. 5, No. 1, February 2014

and reactance of the FACTS Devices for IEEE 30 bus system and the real time Indian 72 bus system which consists of 15 generator bus, 57 load buses .With a view of Incorporating UPFC Controller gives more savings on energy and installment cost comparing SVC and TCSC Controllers.

II. Problem Formulation

The objective function of RPP problem comprises two terms. The first term represents the total cost of energy loss as follows [1]

$$W_C = h \sum_{l \in N_l} d_l p_{loss,l} \tag{1}$$

Where, $P_{loss,}l$ is the network real power loss during the period of load level 1. The $P_{loss,}l$can be expressed in the following equation in the duration d_l:

$$p_{loss} = \sum_{\substack{k \in N_E \\ k \in (i,j)}} g_k \left(V_i^2 + V_j^2 - V_i V_j \cos\theta_{ij}\right) \tag{2}$$

The second term represents the cost of FACTS Controllers.Using Simens AG Database,cost[7] function for SVC and TCSC are developed as follows

$C_{TCSC} = 0.0015_S^2 - 0.173_S + 153.75$
$C_{SVC} = 0.0003s^2 - 0.3051s + 127.38$
$C_{UPFC} = 0.0003s^2 - 0.2691s + 188.22$ (3)

The objective function is expressed as

$$M_{in} F_C = W_C + C_{facts} \tag{4}$$

The functions should satisfy the real and reactive power constraints (equality constraints)

(i) Load Flow Constraints:

$$0 = P_i - V_i \sum V_j \left(G_{ij} Cos\theta_{ij} + B_{ij} Sin\theta_{ij}\right) \tag{5}$$

$$0 = Q_i - V_i \sum V_j \left(G_{ij} Sin\theta_{ij} - B_{ij} Cos\theta_{ij}\right) \tag{6}$$

And also satisfy the inequality constraints like reactive power generation,bus voltage and FACTS controller installment as follows

(ii) Generator Reactive Power Capabilty Limit:

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \tag{7}$$

(iii) Voltage Constraints:

$$V_i^{min} \le V_i \le V_i^{max} \tag{8}$$

(iv) FACTS Reactive Power Limit:

$$-100 \le Q_{facts} \le 100 \tag{9}$$

(v) FACTS Reactance Limit:

$$-0.8 X_{Line} \le X_{facts} \le 0.2\, X_{Line} \tag{10}$$

$Q_{FACTS,\,i}$ can be less than zero and if $Q_{FACTS,\,i}$ is selected as a negative value, say in the light load period, variable inductive reactive power should be injected at bus i by the FACTS controllers. $Q_{FACTS,\,i}$ act as a control variable. The load bus voltages V_{load} and reactive power generations Q_g are state variables, which are restricted by adding them as the quadratic penalty terms to the objective function. Equation (4) is therefore changed to the following generalized objective function

$$\text{Min } F_C = F_C + \sum_{i \in N_{Qglim}} \lambda_{Vi}\left(V_i - V_i^{lim}\right)^2 + \sum_{i \in N_{Vlim}} \lambda_{Qgi}\left(Q_{gi} - Q_{gi}^{lim}\right)^2 \tag{11}$$

Subjected to

$$0 = P_i - V_i \sum_{\substack{i \in N_{B-l} \\ j \in N_l}} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right)$$

$$0 = Q_i - V_i \sum_{\substack{i \in N_{PQ} \\ j \in N_l}} V_j \left(G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}\right)$$

Where, λ_{vi} and λ_{Qgi} are the penalty factors which can be increased in the optimization procedure;V_i^{lim} and Q_{gi}^{lim} are defined in the following equations:

$$V_i^{lim} = \begin{cases} V_i^{min} & if\ V_i < V_i^{min} \\ V_i^{max} & if\ V_i > V_i^{max} \end{cases}$$

$$Q_{gi}^{lim} = \begin{cases} Q_{gi}^{min} & if\ \ Q_{gi}^{min} < Q_{gi}^{min} \\ Q_{gi}^{max} & if\ \ Q_{gi}^{max} > Q_{gi}^{max} \end{cases} \tag{12}$$

III. Modelling Of Facts Controllers

SVC ,TCSC and UPFC mathematical models are implemented by MATLAB programming. Steady state model of FACTS controllers in this paper are used for power flow studies

A. TCSC

TCSC, the first generation of FACTS, can control the line impedance through theintroduction of a thyristor controlled capacitor in series with the transmission line. A TCSC [3]is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. In this paper, TCSC is modeled by changing the transmission line reactance as below

$$Xij = Xline + Xrcsc \tag{13}$$

Where, X_{line} is the reactance of transmission line and X_{TCSC} is the reactance of TCSC. Rating of TCSC depends on transmission line where it is located. To prevent overcompensation, TCSC reactance is chosen between -0.8X_{line} to 0.2 X_{line}.

B. SVC

SVC can be used for both inductive and capacitive compensation. In this paper SVC ismodeled as an ideal

DOI: 01.IJEPE.5.1.8

reactive power injection controller at bus i

$$\Delta Q_i = Q_{SVC} \quad (14)$$

C. UPFC

The decoupled model of UPFC is used to provide independent [4,6]shunt and series reactive compensation. The shunt converter operates as a stand alone STATIC synchronous Compensator (STATCOM) and the series converter as a standalone Static Synchronous Series Compensator (SSSC). This feature is included in the UPFC structure to handle contingencies (e.g., one converter failure). In the stand alone mode, both the converters are capable of absorbing or generating real power and the reactive power output can be set to an arbitrary value depending on the rating of UPFC to maintain bus voltage.

IV. Critical Lines And Buses Identification

The Fast Voltage Stability Index (FVSI) is used to identify the critical lines and buses. The line index in the interconnected system in which the value that is closed to 1.00 indicates that the line has reached its instability limit which could cause sudden voltage drop to the corresponding bus caused by the reactive load variation. When the line attain beyond this limit, system bifurcation will be experienced.

A. FVSI Formulation

The FVSI is derived from the voltage quadratic equation at the receiving bus on a two -bus system[8]. The general two-bus representation is illustrated in Figure 1.

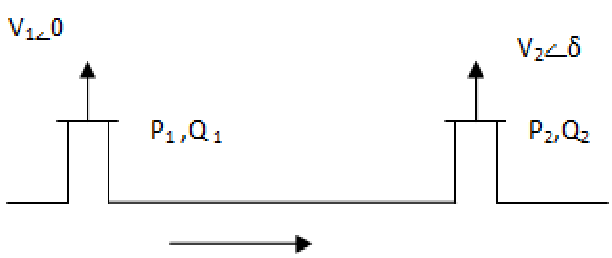

Figure 1: Representation of Two-bus power system

From the figure, the voltage quadratic equation at the receiving bus is written as

$$V_2^2 - \left[\frac{R}{X}\sin\delta + \cos\delta\right] V_1 V_2 + \left(X + \frac{R^2}{X}\right) Q_2 = 0 \quad (15)$$

Setting the equation of discriminant be greater than or equal to zero yields

$$\left(\left[\frac{R}{X}\sin\delta + \cos\delta\right] V_1\right)^2 - 4\left(X + \frac{R^2}{X}\right) Q_2 \geq 0 \quad (16)$$

Rearranging (16), we obtain

$$\frac{4 Z^2 Q_2 X}{V_1^2 (R\sin\delta + X\cos\delta)^2} < 1 \quad (17)$$

since"i"as the sending bus and "j" as the receiving end bus,Since δ is normally very small, then, $\delta \approx 0$, $R\,Sin\delta \approx 0$ and $X\ cos\,\delta = X$ .Taking the symbols i as the sending end bus and j as the receiving bus, FVSI can be defined by

$$FVSI_{ij} = \frac{4z^2 Q_j}{V_i^{\,2} X} \quad (18)$$

Where z and x is the line impedance and reactance, Q_j is the reactive power at the receiving end, and V is the sending end voltage.

B. Identification of Critical Lines and Buses

The following steps are implemented.

1.Load flow analysis using Newton Raphson is done.

2.Calculate the FVSI value for each line .Gradually increase the reactive power loading at a selected load bus until load flow solution fails to converge for the maximum FVSI.

3.Extract the maximum reactive power loading for the maximum computable FVSI for every load bus. The maximum reactive power loading is referred as the maximum loadability of a particular bus.

4.Sort the maximum loadability obtained from step 4 in ascending order. The smallest maximum loadabilityis ranked the highest, implying the critical bus and the maximum FVSI value close to one indicates the critical line referred to a particular bus.

5.Select the critical buses and lines to install the FACTS controllers for the stability enhanced RPP problem.

V. Evolutionary Programming

EP is an artificial intelligence method which is an optimization algorithm based on the mechanics of natural selections-mutation, competition and evolution. The general process of EP is described in [1]. The procedure of EP for RPP is briefed as follows

A. Initialization

The initial control variable population is selected randomly from

$p_{i=} [V_{PV}^{\,i}, Q_c^{\,i}, T^i]$, i=1,2,……..,m,

where m is the population size, from the sets of uniform distribution ranging over $[V^{min}, V^{max}]$,$[Q_c^{\,min}, Q_c^{\,max}]$ and $[T^{min}, T^{max}]$. The fitness score is obtained by running Newton –Raphson power flow.

B. Statistic

The values of maximum fitness, minimum fitness, sum of fitness and average fitness of this generation are calculated.

C. Mutation

Each pi is muted and assigned to P_{i+m} in accordance with the following equation

$$P_{i+m,j} = P_{i,j} + N\left(0, \beta (x_{jmax} - x_{jmin}) \frac{f_i}{f_{max}}\right), j=1,2,\text{—}n \quad (19)$$

Where, P_{ij} denotes j^{th} element of the i^{th} individual. $N(\mu,\sigma^2)$ represents a Gaussian random variable with mean μ and variance σ^2 ; f_{max} is the maximum fitness of the old generation which isobtained in statistics. $x_{j\,max}$ and $x_{j\,min}$ are the maximum and minimum limits of the j^{th} element. β is the mutation scale which is given as 0 <β d"1. If any $P_{i+m,j}$,j=1,2 ……n, where n

DOI: 01.IJEPE.5.1.8

is the number of control variables, exceeds its limit, $P_{i+m,j}$ will be given the limit value. The corresponding fitness f_{i+m} is obtained by running power flow with P_{i+m} . A combined population is formed with the old generation and the mutated old generation.

D. Competition

Each individual, $P_i$in the combined population has to compete with some other individuals to get its chance to be transcribed to the next generation.

E. Determination

The convergence of maximum fitness to minimum fitness is checked. If the convergence condition is not met, the mutation and competition processes will run again.

VI. New Improved Modified Differential Evolution (Nimde)

The main idea of original DE is to generate trial parameter vectors using vector differences for perturbing the vector population [9,10, 11].In order to improve the performance of differential evolution ,the first modification is proposed novel algorithm[17] which will generate a dynamical function for changing the differential evolution parameter mutation factor replace traditional differential differential algorithm use constant mutation factor.

A. Main Steps of the NIMDE Algorithm

The working procedure [17] algorithm is outlined below:
1.Initialize the population set uniformly.
2.Sort the population set S in ascending order,
3.partition S into *p* sub populations $S^1,S^2,\ldots,S^p$
Each containing m points,such that;
$S^k = \{ X_j^k, f_j^k : X_j^k = X_{k+p(j-1)}, f_j^k = f_{k+p(j-1)}, j = 1,\ldots,m \}$
K= 1,…,p
4.Apply improved DE[17] algorithm to each sub population S^k to maximum number of generation $G_{max.}$
5.Replace the sub populations $S^1,S^2,\ldots S^p$ and check whether the termination criterian met if yes then stop otherwise go to step 2.
4.Mutation .select variable vectors and acquire their difference and multify the F value from F value function.produce the dononr vector at the end.F is used randomly and their limit [-1,0.4]U[0,4.1] for each mutated point.

B. NMIDE Implementation for Load Flow

The chromosome structure of NMIDE is defiend P_G, Q_G and Tranformer Tap setting.The control variables are self constrained.To handle inequality constraints of state variables ,including slack bus real and reactive power ,load bus voltage magnitudes ,fitness function is considered equations (11) and (12).

VII. Optimal Parameter Values

The performance of NIMDE and EP algorithms are greatly influenced by values of their parameters.Therefore proper selection of values of values of parameter is vital.The algorithms are run several times and parameters are tuned for the optimum performance of the algorithms.The most suitable values obtained for the objectives considered are tabulated in Tables I and II.

Table I. Optimal Values of EP Parameter

parameter	Optimal values
No.of Individuals	20
Mutation Constant	0.3
No.of Iterations	300

Table II. Ooptimal Values of NIMDE Parameter

parameter	Optimal values
No.of Individuals	20
Scaling Factor	0.5
Cross Over constant	0.4
No.of Iterations	300

VIII. Numerical Results

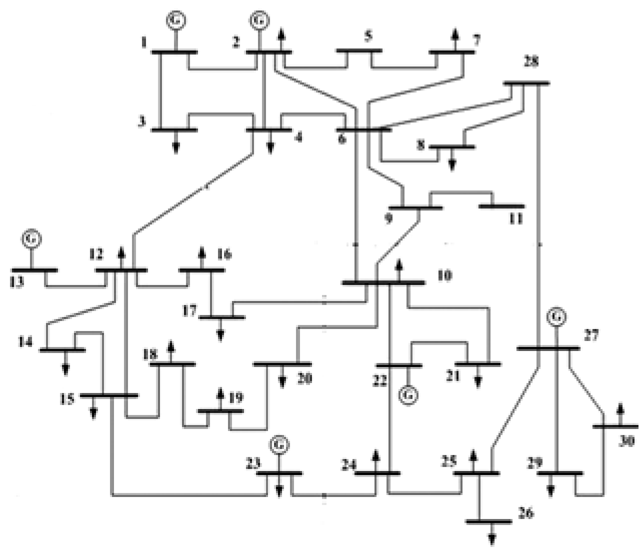

Figure 2: IEEE 30 bus system

Simulation results have been obtained by using MATLAB (R2009b) software package .Figure 2.shows the IEEE 30 bus system has been used to show the effectiveness of the algorithm has been illustrated in .using medium seized IEEE 30 bus system [15].The loading is taken,Normal,1.25% loading and 1.5% loading. The duration of the load level is 8760 hours in both cases [2].The system has 6 generator buses (1 Slack and 5 *PV* buses),24 load buses,and 41 Transmission lines.Transmission lines 6-9,6-10,4-12, and 28-27 have tap changers.

A. Initial Power Flow Results

The initial generator bus voltages and transformer taps are set to 1.0 pu. The loads are given as,
Case 1: P_{load} = 2.834 and Q_{load} = 1.262
Case 3: P_{load} = 4.251 and Q_{load} = 1.893

As shown in Table III, FACTS devices are located in the global best positions and results were obtained both approaches for the Case-1 and Case-3 using NIMDE adjusted the voltage magnitude of all PV buses and transformer tap settings such that total Real and Reactive power losses decreased comparing EP.

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TABLE III. COMPARISION RESULTS

Variables	Case-1		Case-3	
	NMIDE	EP	NMIDE	EP
V1	1.05	1.05	1.05	1.05
V2	1.044	1.044	1.022	1.022
$T_{6\text{-}9}$	1.05	1.0433	0.9	1.013
$T_{4\text{-}12}$	0.975	1.031	0.95	0.973
$Q_{C\,17}$	0	0	0.0229	0.297
$Q_{C\,27}$	0	0	0.196	0.297
P_G	2.866	2.989	5.901	4.659
Q_G	0.926	1.288	2.204	2.657
P_{loss}	0.052	0.159	0.233	0.417
Q_{loss}	0.036	0.266	0.436	1.190

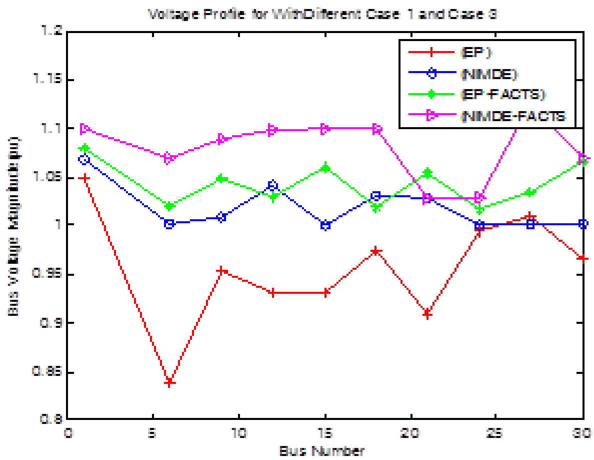

Fig 3.Voltage profile improvement for case-1 and case-3

EP-Bus Voltage Magnitude with out FACT Device for 100% Load

NMIDE- BusVoltage Magnitude with UPFC for 100% Load

EP-FACTS-BusVoltage Magnitude with UPFC for 1.5% Load using EP

DE-FACTS-Bus Voltage Magnitude with UPFC for 1.5% Load using NIMDE

Figure 3.Illustrated Bus Number Vs Bus Voltage Mangitude and it shows that DE approach with FVSI give better voltage magnitude comparing EP.

IX. CASE STUDY

Simulation results have been obtained by using MATLAB (R2009b) software package .IEEE 72 bus system has been used to show the effectiveness of the algorithm.The system h as 15 Generator Buses and 55 loadbuses. FACTS locations are identified based on the FVSI technique. The maximum loadability and FVSI values for the real time system are given in Table IV.

From the Table, bus 25 has the smallest maximum loadability implying the critical bus and the branch 26 – 38 has the maximum FVSI value close to one indicates the critical line referred to bus 38. Hence, SVC is installed at bus 25, TCSC is installed in the branch 26 to 38.UPFC installed at midpoint of branch 26 to 38.The parameters and variable limits are listed in Table 5. All power and voltage quantities are per-unit values and the base power is used to compute the energy cost.

Two cases have been studied. Case 1 is the light load. Case 2 is of heavy loads whose load is 125% as those of Case 1. The duration of the load level is 8760 hours in both the cases.

TABLE IV: BUS RANKING AND FVSI VALUES

Rank	Bus	Q_{max}(p.u)	FVSI
1	25	0.23	0.9837
2	27	0.27	0.9841
3	56	0.28	0.9964
4	52	0.35	0.9925
5	45	0.43	0.9843
6	59	0.45	0.9932
7	37	0.47	0.9972
8	46	0.48	0.9887
9	68	0.56	0.9863
10	64	0.57	0.9897
11	30	0.59	0.9852
12	29	0.63	0.9922
13	36	0.658	0.9787
14	49	0.67	0.9858
15	55	0.71	0.9871
16	19	0.712	0.9936
17	17	0.732	0.997
18	53	0.74	0.9856
19	16	0.77	0.9879
20	61	0.81	0.9989
21	18	0.85	0.9947
22	57	0.856	0.9937
23	26	0.87	0.9859
24	23	0.881	0.9986
25	33	0.893	0.9783
26	48	0.9	0.9949
27	34	0.911	0.9929
28	59	0.925	0.9893
29	51	0.96	0.9801
30	40	0.962	0.9857
31	42	0.982	0.9862
32	38	0.988	0.9999
33	22	0.99	0.9931
34	43	1.01	0.9976
35	19	1.1	0.9798
36	32	1.13	0.998
37	18	1.19	0.9879
38	41	1.22	0.9899
39	52	1.27	0.9871
40	45	1.3	0.9759
41	54	1.34	0.9795
42	28	1.354	0.9889
43	26	1.378	0.9567
44	60	1.39	0.9854
45	21	1.415	0.9912
46	59	1.42	0.9877
47	44	1.47	0.9945
48	47	1.51	0.9947
49	50	1.54	0.9858
50	20	1.59	0.9857
51	31	1.61	0.9982
52	36	1.75	0.9865
53	32	1.61	0.9789
54	39	1.88	0.9658
55	69	1.93	0.9687
56	66	1.98	0.9723
57	46	2.03	0.9834

TABLE V: PARAMETERS AND LIMITS

Base MVA		h($/puWh)	
100		6000	
V_g		V_{load}	
min	max	min	max
0.9	1.1	0.95	1.05

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A. Initial Power Flow Results

The initial generator bus voltages and the loads are given as,

Case 1: P_{load} = 2.7821 and Q_{load} = 1.1890

Case 2: P_{load} = 3.49865 and Q_{load} = 1.4568

TABLE VI: OPTIMAL GENERATOR BUS VOLTAGES

BUS	Case 1			Case 2		
	SVC	TCSC	UPFC	SVC	TCSC	UPFC
1	1.0999	1.0999	1.0999	1.0999	1.0999	1.0999
12	1.0859	1.0876	1.0821	1.0994	1.0982	1.0977
15	1.0951	1.0924	1.0857	1.0999	1.0988	1.0884
24	1.0994	1.0897	1.0791	1.0996	1.0874	1.0741
35	1.0854	1.0796	1.0774	1.0802	1.0784	1.0721

FACTS device settings, optimal generator bus voltages and optimal generation and power losses are obtained as in Table VI to VIII.

TABLE VII: FACTS DEVICE SETTINGS

Parameters	FACTS Location	Case 1	Case2
X_{TCSC}	26-28	-0.1672	-0.08006
Qsvc	Bus 30	0.2	0.2
Q_{UPFC}	26-28	0.1974	0.29421
X_{UPFC}	26-28	-0.0432	-0.06732

TABLE VIII: OPTIMAL GENERATIONS AND POWER LOSSES

		P_g	Q_g	P_{Loss}	Q_{Loss}
Case 1	SVC	3.0017	1.0994	0.1655	0.3054
	TCSC	2.9895	1.3678	0.1642	0.2849
	UPFC	2.9876	1.1644	0.1639	0.2651
Case 2	SVC	3.8965	1.8159	0.2976	0.7781
	TCSC	3.8724	1.8043	0.2835	0.7054
	UPFC	3.8701	1.7975	0.2687	0.6827

TABLE IX: PERFORMANCE COMPARISION

		P_{Csave} %	$W_{C\ Save}$ ($)
Case 1	SVC	8.98276	872799.60
	TCSC	9.80755	909185.60
	UPFC	9.98894	962585.58
Case 2	SVC	10.0464	164724.50
	TCSC	14.4610	2373163.00
	UPFC	16.6511	3169977.04

Performance comparison of the FACTS controllers are given in Table 9. From the comparison, the UPFC gives more savings on the real power and annual cost compared to SVC and TCSC for both cases.

Figure 4.Illustrated the response for Bus Number Vs.Bus voltage magnitude.From plot,using NMIDE approach for Case 2 with FVSI,UPFC controller gives the better voltage magnitude comparing TCSC and SVC.

X. CONCLUSION

The work presents the successful analysis on Incorporating FACTS controller UPFC in IEEE 30 bus system compared with New Improved Modified Differential Evolution Algorithm and EP algorithm.As a result of that Real and reac-

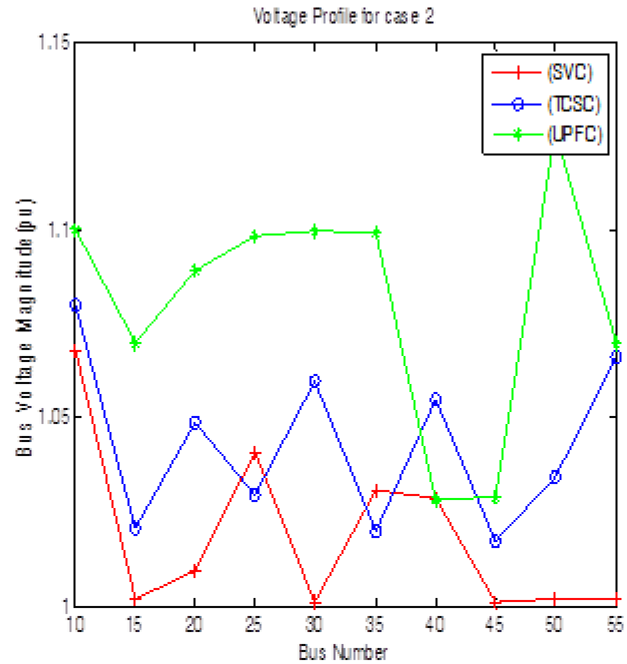

Fig.4.Voltage profile improvent for case 2 uisng FACT Devices

tive power losses are reduced for case 1 and case 3 using NIMDE algorithm.In case study FACTS controllers like SVC,TCSC and UPFC are located in a practical 72 Indian systems which shows the losses are reduced when using UPFC than using SVC and TCSC for case 1 and case 2. By the NIMDE approach with FVSI method, more savings on the energy and installment costs are achieved. Results shows that saving of annual cost is increased using UPFC than SVC and TCSC devices Compared with previous studies.

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